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Efficient Direct-Matching Rectenna Design for RF Power Transfer Applications

Shady Keyrouz[1,2] and Huib Visser[2,1]

[1]Technical University of Eindhoven, Den Dolech 2, 5612 AZ, Eindhoven, The Netherlands.
[2]Holst Centre/imec-nl, High Tech Campus 31, 5656 AE, Eindhoven, The Netherlands.

E-mail: s.keyrouz@tue.nl

Abstract. This paper presents the design, simulation, fabrication and measurements of a 50 ohm rectenna system. The paper investigates each part (in terms of input impedance) of the rectenna system starting from the antenna, followed by the matching network, to the rectifier. The system consists of an antenna, which captures the transmitted RF signal, connected to a rectifier which converts the AC captured signal into a DC power signal. For maximum power transfer, a matching network is designed between the rectifier and the antenna. At an input power level of -10 dBm, the system is able to achieve an RF/DC power conversion efficiency of 49.7%.

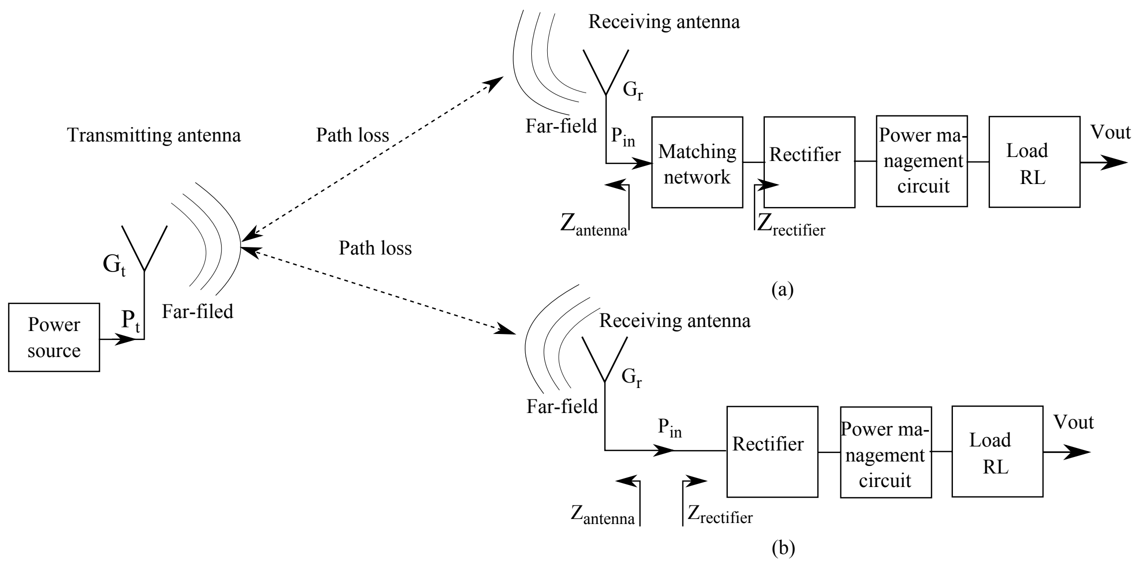


Figure 1. Conventional wireless power transmission systems.

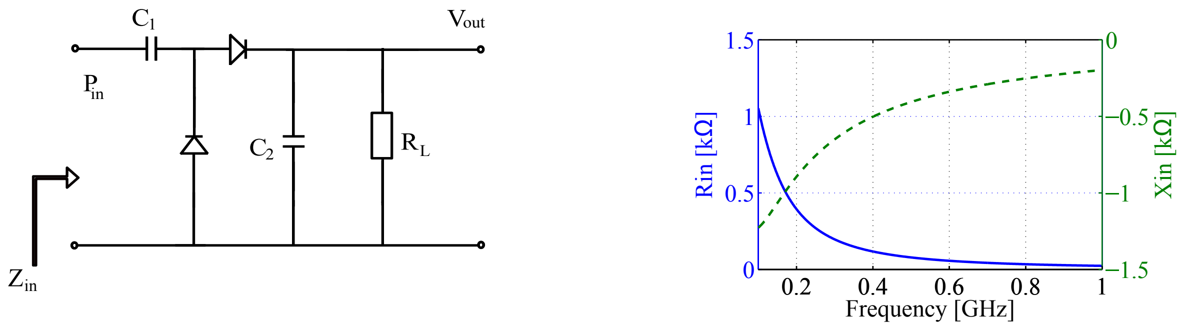
1. Introduction

A conventional far-field RF power harvesting system is shown in Fig.1. The system consists of a transmitter that transmits RF power and a receiver that collects the transmitted power.

When the transmitter is not dedicated for wireless power transmission, e.g. TV and GSM broadcasting, the power collection and conversion is defined as wireless power harvesting [1]. When the power is intentionally transmitted using a dedicated source, this is defined as wireless power transport [2]. For both, the receiving side consists of a rectenna (rectifying antenna) i.e. an antenna connected to a rectifier and a load. A power management circuit between the rectifier and the load is needed to transfer and store the DC power. For a maximum power transfer, a matching network is needed between the antenna and the rectifier as shown in Fig. 1-a. In order to achieve a compact rectenna system, the matching network can be removed as shown in Fig.1-b, and the antenna is conjugately matched to the rectifier ($Z_{antenna} = Z^*_{rectifier}$). In this paper, a standard 50 ohm antenna is matched to the rectifier using a lumped element matching network see Fig1-a.

2. Voltage doubler and matching network

As it is clearly indicated in Fig. 1-a, a rectifier is needed to transform the RF input power into DC power. For maximum power transfer between the antenna and the rectifier, a matching network is designed, simulated, manufactured and measured. Commercially available, discrete schottky diodes HSMS 2852 [3] have been used. ADS harmonic balance and momentum have been used for simulations. The input impedance of the rectifier is simulated at an input power level of -10 dBm and an operating frequency of 868 MHz.

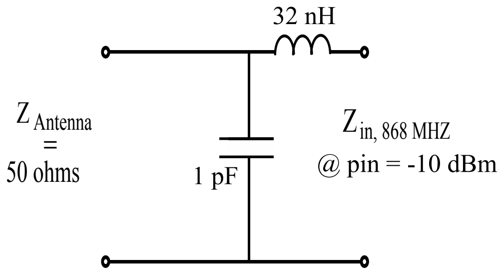


(a) - Voltage doubler configuration

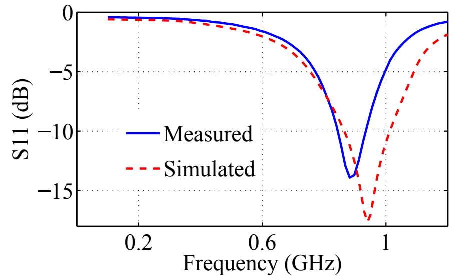
(b) - Voltage doubler impedance

Figure 2. Voltage multiplier configuration (a) and its input impedance (b) as a function of frequency. Pin = -10 dBm.

Fig. 2-a shows the suggested voltage doubler configuration. C1 and C2 are set to 100 pF. RL is set to 10 kΩ. Zin is the input impedance of the voltage doubler. Since the rectifier is a non linear device and its impedance changes as a function of frequency and as a function of input power level, an input power level of -10 dBm is chosen. Fig. 2-b shows the simulated real (solid curve) and imaginary (dashed curve) parts of the input impedance as a function of frequency. At an operating frequency of 868 MHz, the impedance of the voltage doubler is found to be 27- j222 Ω. A matching network is designed to transform this impedance to 50 ohms. Fig. 3-a shows the suggested lumped elements matching network to match the impedance of the voltage doubler to 50 ohms. The matching network consists of a 32 nH inductor and a 1 pF capacitor. The capacitor is placed in parallel with the antenna ports and the inductor is placed in series with the voltage doubler. Fig. 3-b shows the simulated and the measured reflection coefficients of the fabricated voltage doubler and the matching network as a function of frequency at an input power level of -10 dBm. It is clear from the measurement results that the designed matching network will match the impedance of the voltage doubler to that of the antenna at 868 MHz.



(a) - Designed matching network

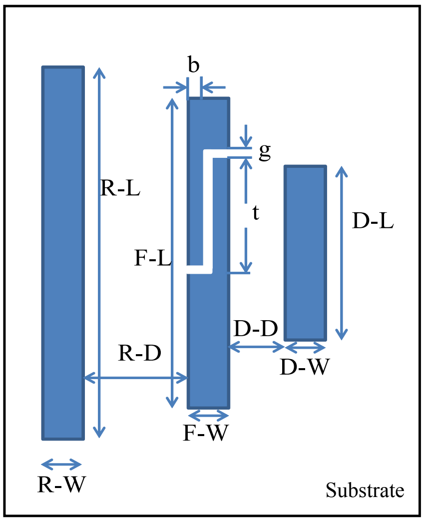


(b) - Simulated and measured S11

Figure 3. Designed and manufactured (a) lumped element matching network and its reflection coefficients (b) vs. frequency.

3. Standard 50 ohm antenna design

This section presents the optimization and the design of a modified 50 ohm Yagi-Uda antenna that will be used to harvest RF power. The antenna was first introduced in [4] and used to harvest RF power from DTV signals. The main advantage of such an antenna, is that by tuning its parameters it can behave like a broadband, dual-band or a multi-band antenna [5]. The antenna is designed to resonate within the frequency band 850 MHz to 1 GHz. Fig. 4-a shows the suggested antenna configuration to cover the required frequency band. The optimized parameters are shown in Fig. 4-b.



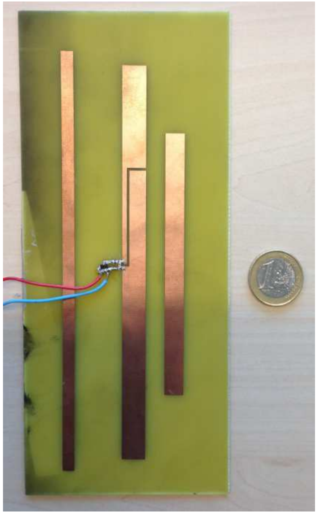
(a) - Suggested antenna configuration

Parameter	(mm)
D-L	106
D-W	8
D-D	8
R-L	167
R-W	5
R-D	20
F-L	158
F-W	10
t	39
b	2
g	1

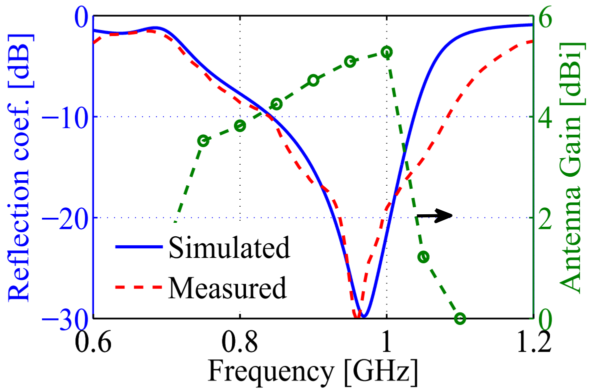
(b) - Optimized parameters

Figure 4. (a) Suggested broad-band modified Yagi-Uda antenna and (b) its optimized parameters.

The antenna is designed, simulated and manufactured on a 1.6 mm FR4 substrate. The fabricated antenna is shown in Fig.5-a. The reflection coefficient of the fabricated antenna is measured between 600 MHz and 1.2 GHz using the Agilent PNA-X Network Analyser. The simulated (solid curve) and measured (dashed curve) reflection coefficient as a function of frequency are shown in Fig.5-b. It is clear form the figure that the measured reflection coefficients agree well with the simulated ones, which validates the simulated results. In addition, Fig. 5-b shows the simulated antenna gain (dashed-dotted curve), the simulated antenna gain is 4.23 dBi at an operating frequency of 868 MHz. This antenna gain will be used to calculate the Power Conversion Efficiency (PCE) of the rectenna.



(a) - Fabricated rectenna system



(b) - S11 and antenna gain

Figure 5. (a) Manufactured rectenna (b) its reflection coefficients and antenna gain.

4. RF power transport

The setup is calibrated using two identical antennas with a known gain at 868 MHz separated by 1 meter ensuring far-field conditions. A power meter and a spectrum analyzer were used to measure the available RF power. The measured power is within within ± 0.5 dB agreement with the theoretically calculated available power. The receiving rectenna system shown in Fig. 5-a consists of the antenna introduced in the previous section connected to a rectifier and to a variable load resistor RL. The DC output voltage is measured for different load resistances at an input power level of - 10 dBm. The available power $P_{available}$ on the receiving antenna terminal is expressed by:

$$P_{available} = P_T - L_P + G_T = EIRP - L_P, \quad (1)$$

P_T is the transmitted power, G_T is the maximum gain of the transmitting antenna. The product $G_T P_T$ is called the Effective Isotropic Radiated Power (EIRP). L_P is the free space path loss,

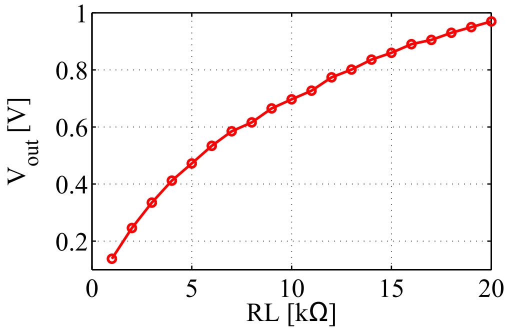
$$L_P(dB) = 32.44 + 20 \times \log(f) + 20 \times \log(R), \quad (2)$$

where f is in MHz and R is in km. The input power level P_{in} on the rectifier terminals is :

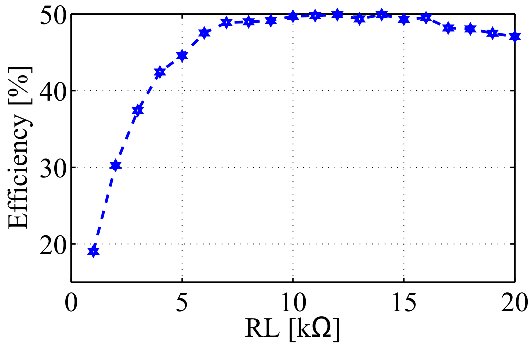
$$P_{in}(dBm) = P_{available}(dBm) + G_R, \quad (3)$$

where G_R is the gain of the receiving antenna.

Fig.6-a shows the measured output voltage vs. load resistance at an input power level of -10 dBm at an operating frequency of 868 MHz. The system output voltage reaches 0.705 V over 10 kΩ load resistance. The PCE is calculated using eq. 4 and is shown in Fig.6-b. The system PCE reaches 49.7 % over 10 kΩ load resistance. Compared to the state of the art, [6], [7] and [8]



(a) - Measured output voltage



(b) - Mesured PCE

Figure 6. (a) Rectenna output voltage (b) its measured Power Conversion Efficiency (PCE).

the proposed rectenna in this paper shows higher efficiency performance. Compared to [9] our suggested rectenna achieves almost similar PCE performance at the same input power level.

$$PCE\,(\%) = \frac{P_{load}}{P_{in}} = \frac{V_{out}^2}{R_L}\frac{1}{P_{in}} \tag{4}$$

5. Conclusion

In this paper a standard 50 ohm rectenna system has been presented. Each sub-part of the rectenna system (antenna, matching network and rectifier) has been investigated independently. For maximum power transfer, a matching network is designed between the rectifier and the antenna. The system has been manufactured and tested. At an input power level of -10 dBm, and an operating frequency of 868 MHz, over a 10 kΩ load resistance,the system output voltage reaches 0.705 V and the RF/DC power conversion efficiency reaches 49.7%.

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